LPP Source System Development for HVM

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ABSTRACT

Laser produced plasma (LPP) systems have been developed as a viable approach for the EUV scanner light sources to support optical imaging of circuit features at sub-22nm nodes on the ITRS roadmap. This paper provides a review of development progress and productization status for LPP extreme-ultra-violet (EUV) sources with performance goals targeted to meet specific requirements from leading scanner manufacturers. The status of first generation High Volume Manufacturing (HVM) sources in production and at a leading semiconductor device manufacturer is discussed. The EUV power at intermediate focus is discussed and the lastest data are presented. An electricity consumption model is described, and our current product roadmap is shown.

Keywords: EUV source, EUV lithography, Laser Produced Plasma

1. INTRODUCTION

EUV Lithography is the front runner for next generation critical dimension imaging after 193 nm immersion lithography for layer patterning below the 22 nm node; beginning in 2013 according to the International Technology Roadmap for Semiconductors (ITRS). NAND Flash and DRAM devices are expected to have the need for this manufacturing technology as soon as 2012, with pilot line system introduction starting this year (2011). The availability of high power 13.5 nm sources has been categorized as high risk and ranked as critical with other technologies requiring significant developments to enable the realization of EUV lithography. High sensitivity photoresists with good line-edge-roughness (LER) and line-width-roughness (LWR) are needed to keep the required source power within reasonable limits. Photoresist sensitivity and overall optical transmission through the EUV scanner are the basis to derive EUV source power requirements within the usable bandwidth (BW) of 2 %. Scanner manufacturers are requiring clean EUV power of 250W at the intermediate focus (IF) to enable > 100 wph scanner throughput assuming a photoresist sensitivity of 15 mJ/cm^2. The need for an IR spectral purity filter (SPF) increases the requirements for raw EUV Power even further.

Clean EUV Power is calculated by taking the raw EUV power and subtracting the losses associated with the spectral purity filter (SPF) and the dose control overhead; for current HVM I sources these losses are estimated to be 35% and 20%, respectively. A scalable EUV source architecture is needed to enable the evolution of EUV lithography during the life cycle of the technology. Laser-produced-plasma (LPP) sources are expected to deliver the necessary power for critical-dimension high-volume manufacturing (HVM) scanners for the production of integrated circuits in the post-193 nm immersion lithography era.[1]

LPP EUV lithography light sources generate the required 13.5 nm radiation by focusing a 10.6 micron wavelength CO_2 laser beam onto tin (Sn) targets creating a highly ionized plasma with electron temperatures of several 10's of eV. EUV photons are radiated isotropically by these ions. Photons are collected with a temperature controlled graded multi-layer coated normal-incidence mirror (collector), and focused to an intermediate point from where they are relayed to the scanner optics and ultimately to the wafer. High conversion efficiency (CE) of the laser energy into EUV energy is critical to meeting the required power levels. The collector is protected from the plasma by a debris mitigation

technology based on a hydrogen buffer gas. High-energy ions, fast neutrals, and residual source element particles are mitigated to maintain the reflectivity of the collector mirror and enable a long lifetime of this component. Diagnostics measuring the properties of emitted light at both the plasma and IF are used to characterize the output of the source.[2] Performance results of test and prototype light sources obtained up to about a year ago have already been described in detail previously.[1,3,4,5]

2. LPP SOURCE SYSTEM

The system architecture is shown in a scale drawing in Figure 1. The three major subsystems of the source are the drive laser, the beam transport system (BTS) and the source vessel. The drive laser is a CO_2 laser with multiple stages of amplification to reach the required power level of up to ~30 kW.[1,6] It is operated in pulsed mode at ~50 kHz with radio-frequency (RF) pumping from generators (not shown) operating at 13.56 MHz. The laser is typically installed in the sub-fab along with its RF generators and water-to-water heat exchangers. The laser beam is expanded as it leaves the drive laser to lower the energy density on the BTS mirrors. Three turning mirrors are used to allow the beam to travel from the sub-fab to the fab through the waffle-slab floor with the needed flexibility for positioning the laser with respect to the source vessel (and scanner) on the floor above. The laser and BTS are completely enclosed and interlocked to meet laser class 1 requirements. The BTS delivers the beam to a focusing optic where the 10.6 micron wavelength light is focused to a minimum spot size defined by the numerical aperture of the focusing system. The focused beam propagates through a central aperture in the collector and strikes the droplet at the focus of the ellipsoidal collector mirror inside the vacuum space of the source vessel. The droplet generator delivers liquid tin droplets of 30 micron diameter to the same position at ~ 50 kHz repetition rate; both laser pulse and droplets are steered and timed to ensure proper targeting. The laser pulse vaporizes and heats the tin into a plasma cloud of critical temperature and density. The EUV light emitted by the plasma is collected and reflected with the multi-layer coated ellipsoidal mirror to the IF where it passes through a small aperture into the scanner volume that houses the illumination optics.

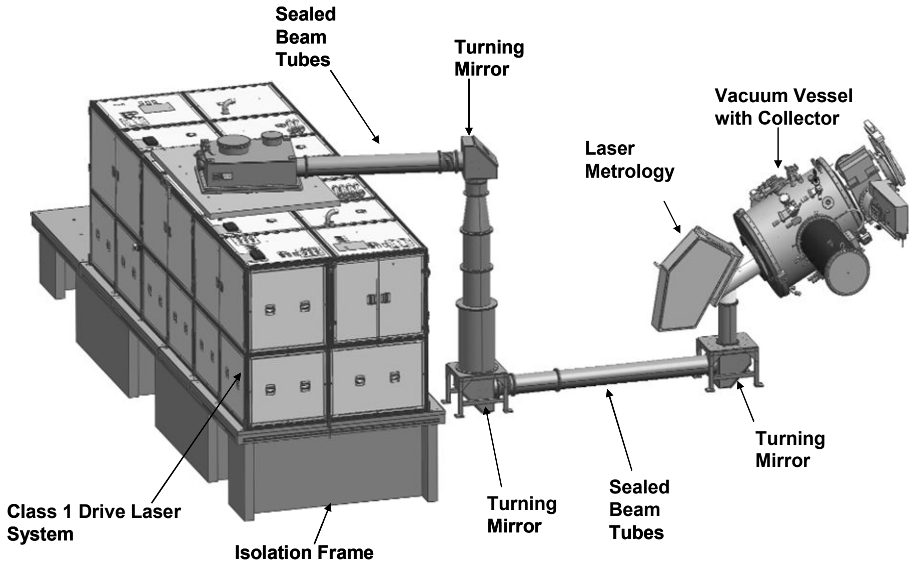

Figure 1: Scale Drawing of Laser Produced Plasma Source.

To ensure that no contamination can reach the scanner volume an IF protection module surrounds the aperture and suppresses flow or diffusion. Other modules on the source vessel include the droplet catcher which collects the unused droplets between the bursts, and metrology modules for measuring EUV energy and for imaging of droplets and plasma. The source controller turns on and off bursts of pulses as commanded by the scanner, which can be as long as several seconds. Exposures at full source power correspond to typically several hundred milliseconds for a 26 x 33mm field size

using 15 to 20mJ/cm^2 resist. The ratio of time when the burst is on to the period between bursts defines the intra-field duty cycle.

Eight first-generation HVM I sources have been completed and are operational. Four of these sources have been installed at customers, including one at a leading semiconductor device maker R&D facility. An HVM I source vessel is shown in Figure 2 positioned at the specified source orientation angle.   Figure 3 shows this source vessel integrated into the NXE 3100 scanner and fully enclosed inside the body of the system.

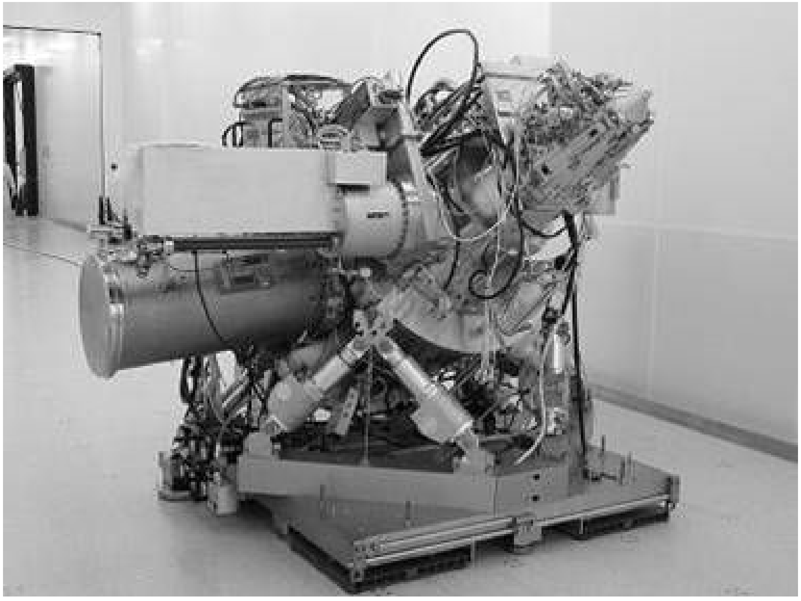

Figure 2: HVM I LPP Source Vessel moving into the customer clean room.

Figure 3: HVM I LPP Source Vessel Integrated into the NXE 3100 Scanner.

3. RECENT DEVELOPMENT RESULTS

Figure 4 shows the dose controlled EUV energy per burst measured on an HVM I source running at ~50% duty cycle, as determined from measurements at plasma. The usable average exposure power is ~11W, as calculated using the assumptions of 5sr solid angle, 50% collector reflectivity, 90% gas and 65% SPF transmission. The feasibility of dose stability meeting the final production requirement of <±0.20% 3σ has been demonstrated, as can be seen in Figures 4 and 5. The data shown is within wafer in Figure 4 and within exposure field in Figure 5. The processing of the data in this way is possible because the source was being driven in a scanner simulation mode during these exposures to replicate the on/off cycling from exposing fields and waiting for the scanner to move to the next field. .

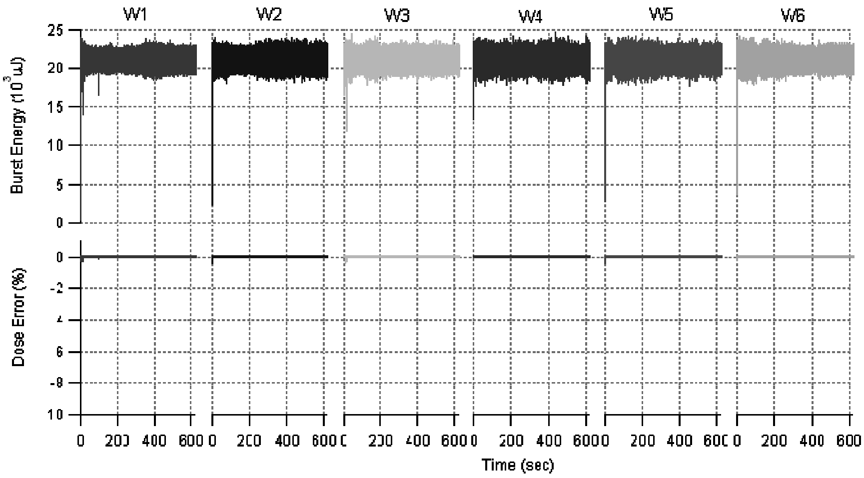

Figure 4: Dose controlled EUV energy within wafer (upper chart), 6 wafers: Dose stability within wafer (lower chart)

This scanner simulator is a control system emulating a real scanner in a control rack interfaced with our source during testing while the sources are in San Diego. These experiments were performed using tin droplets with 30 micron diameter at 40kHz repetition rate and a nominal 5 seconds per exposure field on one of our HVM I sources. This level of performance will provide a throughput of approximately 6 wafers per hour on an NXE 3100 scanner when using a photoresist sensitivity of 10mJ/cm^2

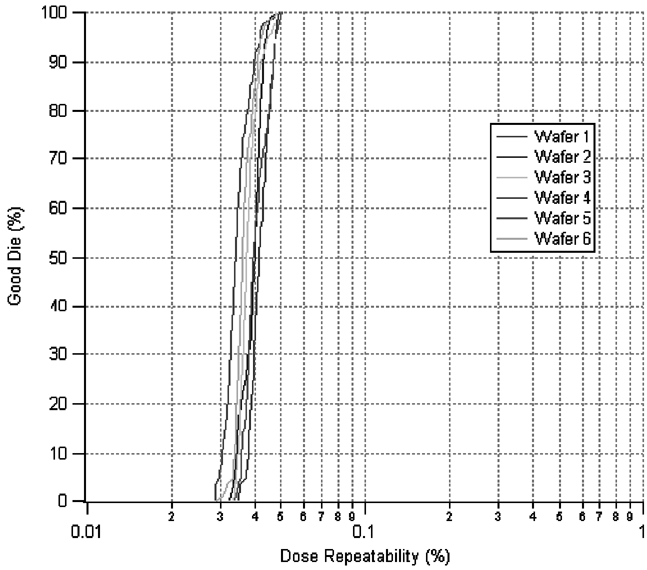

Figure 5: Dose stability distribution within exposure field for 6 wafers

The average area-weighted EUV reflectivity of ten new collectors was measured to be up to 52.1%, see Figure 6 for reflectance results. Several long duration tests have been performed to evaluate the collector protection capability of HVM I sources. Relative reflectivity is monitored using the FFTT during testing to evaluate the efficiency of protection, the difference between the first two data sets (Sept 2010 vs. Feb 2011) demonstrates new gas flow balancing techniques over 50 hours duration , as shown in Figure 7, as was described in the talk at Advanced Lithography.

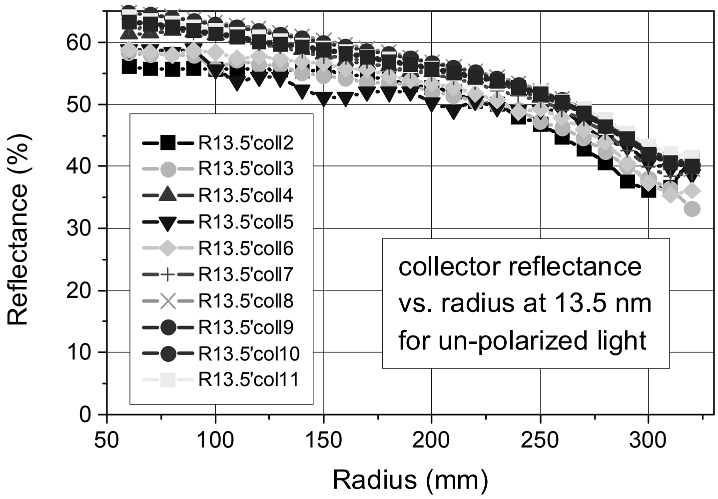

Figure 6: EUV Reflectivity of new Collectors vs. Mirror Radius as measured on a beam line at PTB

Also shown in Figure 7 are more recent results from a 90 hours test using improvements to the coating technology as discussed in the talk. The March 2011 results indicate no degradation of relative reflectivity while delivering a dose of >4MJ to the IF. 4MJ corresponds to approximately 512 wafers or 5.7 wafers per hour assuming 10mJ/cm^2 resist sensitivity and current assumptions for SPF and scanner transmission. Relative average reflectivity vs. exposure dose at IF is plotted in the graph. The data from September 2010 (open squares) was taken during operation at a nominal 6W of average EUV exposure power, while the data from February 2011 (open circles) was taken during operation at 11W power.

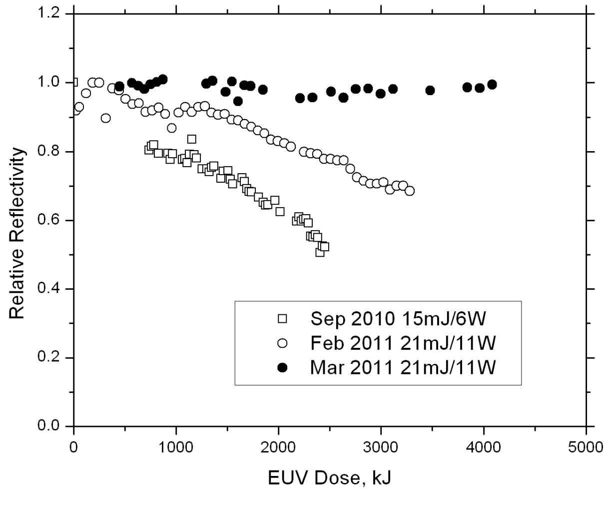

Figure 7: Relative Reflectivity measured during Exposure for three different tests

The newer data (dark circles) shows a significantly reduced reflectivity loss during exposure and is a result of improvements made in the overall protection for the multilayer coating on the surface of the normal-incidence collector. Further improvements are planned to be implemented during 2011 in the areas of gas flow uniformity, vacuum environment cleanliness and multilayer coatings to enable the source to provide an expected collector lifetime of several months and ultimately one year.

Development of our pre-pulse sub-system was completed on our LT1 source for research and development[7]. The pre-pulse expands the droplet target to a larger size and lowers the density before the main pulse irradiates it at the primary focus of the collector. The raw EUV power produced using pre-pulse on LT1 was approximately 160W during operation at 40kHz repetition rate, as shown in Figure 8. The data was collected at low duty cycle (~3%) with no dose control.

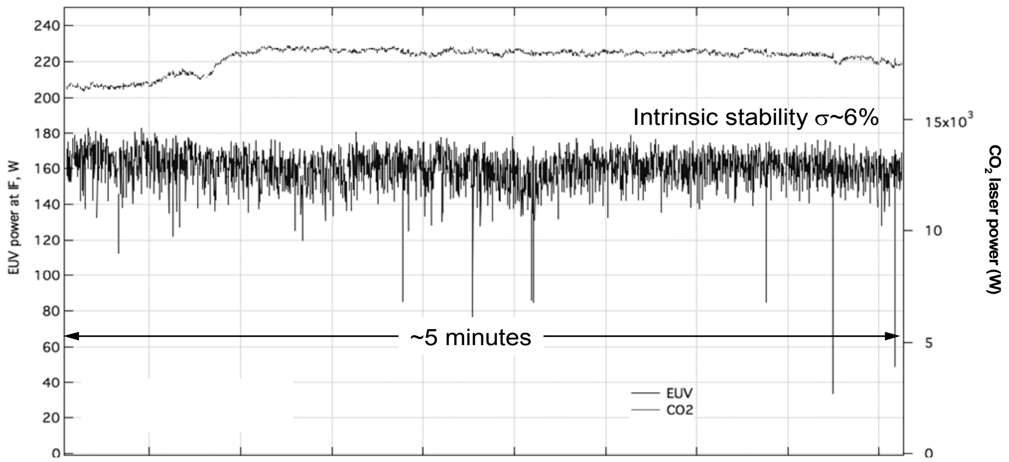

Figure 8: Pre-Pulse Operation on LT1

The CO_2 laser power was approximately 17.5 kW as shown by the second line on the graph in figure 8, corresponding to roughly 3% conversion efficiency (CE), as shown in Figure 9. The pre-pulse sub-system is currently integrated onto an HVM I source in San Diego and being tested in order to determine the optimum operating conditions and maximum usable power when running under high duty cycle and dose-controlled conditions.

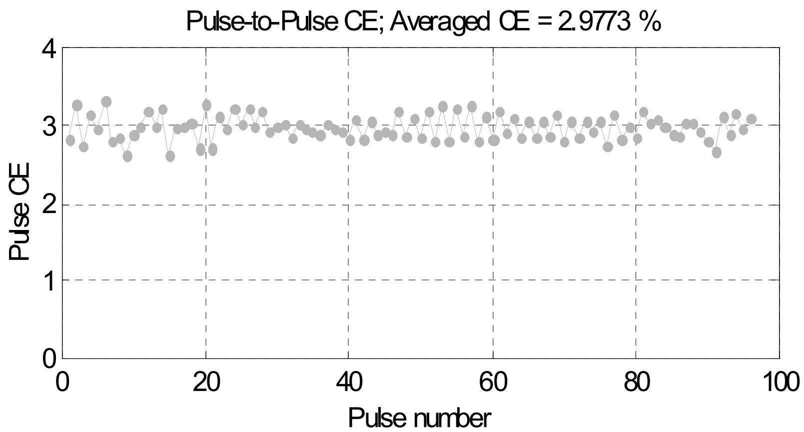

Figure 9: Pulse-to-Pulse Conversion Efficiency

Each of the eight HVM I sources is planned to be upgraded with the pre-pulse subsystem in the fourth quarter of 2011. The sources as shipped have reserved space for this additional hardware to fit within the existing footprint of the drive laser. With this upgraded configuration the HVM I sources are expected to provide the final specification for power output of 105W average exposure power.

4. ELECTRICITY CONSUMPTION

A major utility for the EUV source is the electrical power that the system requires. With the operation of the EUV source at nominal scanner operating conditions we can estimate with reasonable certainty the amount and cost of the electrical power used. These calculations are shown in Figure 10. The histogram for HVM II sources shows decreasing cost of electrical consumption due to higher efficiency of the solid-state RF generators planned to be used on these sources in addition to a lower overall use of a higher power EUV source. The percentage of burst on-time required for the exposure is decreased as the power of the source is increased, resulting in a lower usage of electrical consumption and a lower cost. It should be noted that the cost of electricity consumption used here was based on 0.09 $/kWhr. .

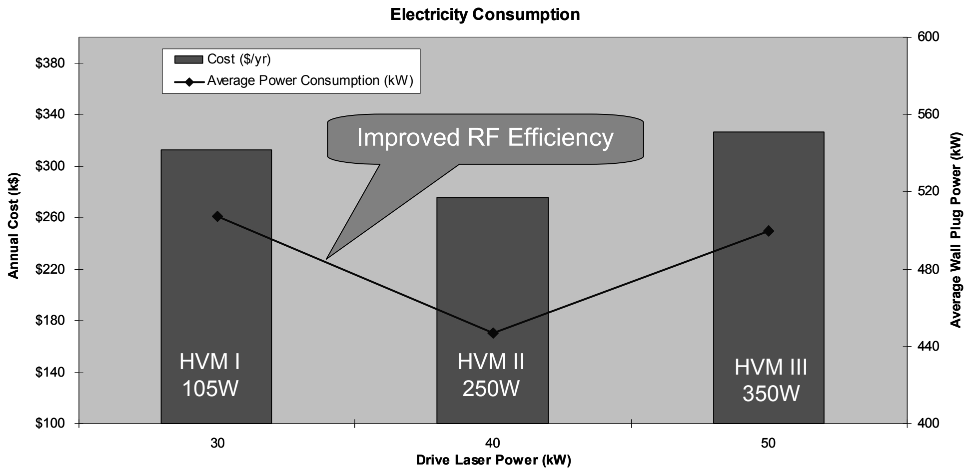

Figure 10: Estimated usage and cost of electrical power for EUV sources

5. ROADMAP

The LPP source roadmap is shown in Figure 11. The HVM I product is expected to meet requirements for pre-production or beta generation scanners in 2011 with clean EUV output powers of >100 W using a 30 kW CO_2 laser system on 30 micron diameter Sn droplets with 3.0 % CE. The normal-incidence collectors used have a collection solid angle of ~ 5 sr and multilayer coatings with EUV reflectivity > 50 % on average over the surface. Transmission losses due to gas absorption and debris mitigation techniques are projected to be less than 20 % and SPF losses are expected to be 35%. Scanner roadmap requirements for later generation LPP EUV sources will drive source powers to 350 W (HVM III) with CO_2 laser power delivering ~50 kW of power. Further improvements in CE and collection efficiency are expected to enable clean EUV power levels that meet these requirements.

EUV Source Power Roadmap			
Source Model	HVM I	HVM II	HVM III
Drive Laser Power (kW)	**30**	**40**	**50**
In-band CE (%)	3.0	3.5	4.0
Collection Efficiency (sr)	5	5.5	5.5
Collector Reflectivity (%)	50	50	50
Clean EUV Power (W)	**105**	**250**	**350**

Figure 11: Projected LPP EUV Source Roadmap

6. SUMMARY

Laser-produced plasmas have been shown to be the leading source technology with scalability to meet requirements from leading scanner manufacturers and provide a path toward higher power as the lithography tools evolve over their life cycle. An EUV power of 160W at intermediate focus at low duty cycle has been reported. The feasibility of meeting the dose stability target of <0.2% has been demonstrated. Normal-incidence collector mirrors of diameter > 650mm, with > 5 sr light collection and average reflectivity >50% are produced and integrated into production LPP systems. The combination of 10.6 μm laser light and Sn source element has demonstrated a CE in excess of 3 %. LPP source technology with power levels of 350W is expected to satisfy the IF power requirement projected in the future.

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